ARMY RESEARCH LABORATORY

Polymeric Material Study for the D-Fuze Windshield

Michael S.L. Hollis

ARL-MR-525 JANUARY 2002

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Aberdeen Proving Ground, MD 21005-5066

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Polymeric Material Study for the D-Fuze Windshield

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Abstract

Pursuant to a previous report [1], an effort has been made to continue to find higher performance materials for the design of windshields. A product that the U.S. Army Research Laboratory provides the test and evaluation community is a yawsonde, now termed "diagnostic fuze" or "D-fuze". This device is capable of sensing the inertial environment of a cannon-launched projectile and telemetering the live data to a ground station. In order to telemeter data in flight, the antenna has to radiate through a protective windshield. This windshield is not only transparent to radio frequency radiation but is also a means of ballistic and thermal protection.

A recent flight experiment with a prototype artillery projectile revealed a weakness of the nylon 66 windshields to "blow-by[1]" gases. The windshields were designed to survive aero-pressures attributable to Mach 3 launch and flight with a significant safety factor. However, blow-by effects were never considered.

A cursory study has been performed on selected extruded bar stock polymers, which are readily available without our having to consult a compounding source, for machining windshields for D-fuzes of various geometries. Ultem® 2300 appears to provide the best mechanical, thermal, and electrical properties of the studied polymer materials. However, depending on the thickness of the geometry, a designer may want to reconsider using unfilled Ultem® 1000. The cross section of the geometry reduces to a range near 0.03125 inch; there may not be enough glass fiber to reinforce the polyetherimide matrix. Further literature research indicated that the ogive of the M762 fuze is made from injected molded polyetherimide with 30% glass filler.

1 Propulsion gases that leak past the projectile's obturator. In addition to the air already being pushed by the launching projectile, these gases increase the total pressure on the windshield.

ACKNOWLEDGMENTS

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1. Introduction

Pursuant to an earlier U.S. Army Research Laboratory (ARL) report [1], an effort has been made to find higher performance materials for the design of windshields. A product that ARL provides to the test and evaluation community is a yawsonde, which is now termed "diagnostic fuze" or "D-fuze". This device is capable of sensing the inertial environment of a cannon-launched projectile and telemetering the live data to a ground station. This device, as seen in Figure 1, is normally screwed onto an artillery shell.

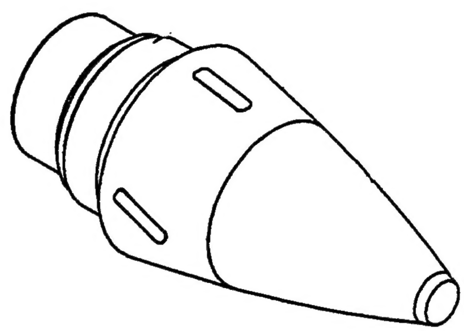

Figure 1. Schematic of a D-Fuze.

In order to telemeter data in flight, the antenna has to radiate through a protective windshield. This windshield is not only transparent to radio frequency radiation but is also a means of ballistic and thermal protection. Figure 2 shows the geometry of the windshield.

A recent flight experiment with a prototype artillery projectile revealed a weakness of the nylon 66 windshields to "blow-by[1]" gases.

The windshields were designed to survive aero-pressures attributable to Mach 3 launch and flight with a significant safety factor. However, blow-by effects were never considered. Previous analysis indicated that the windshield should survive 1000 psi for these effects. This analysis used standard material properties based on certain American Society for Testing Materials (ASTM) standards: ASTM D638 for tensile modulus and D790 for flexural modulus. However, the flight experiment indicated differently. This prompted an investigation into the actual

[1]Propulsion gases that leak past the projectile's obturator. In addition to the air already being pushed by the launching projectile, these gases increase the total pressure on the windshield.

properties of the nylon 66. This report covers the various material experiments to determine a new material for the D-fuze windshield.

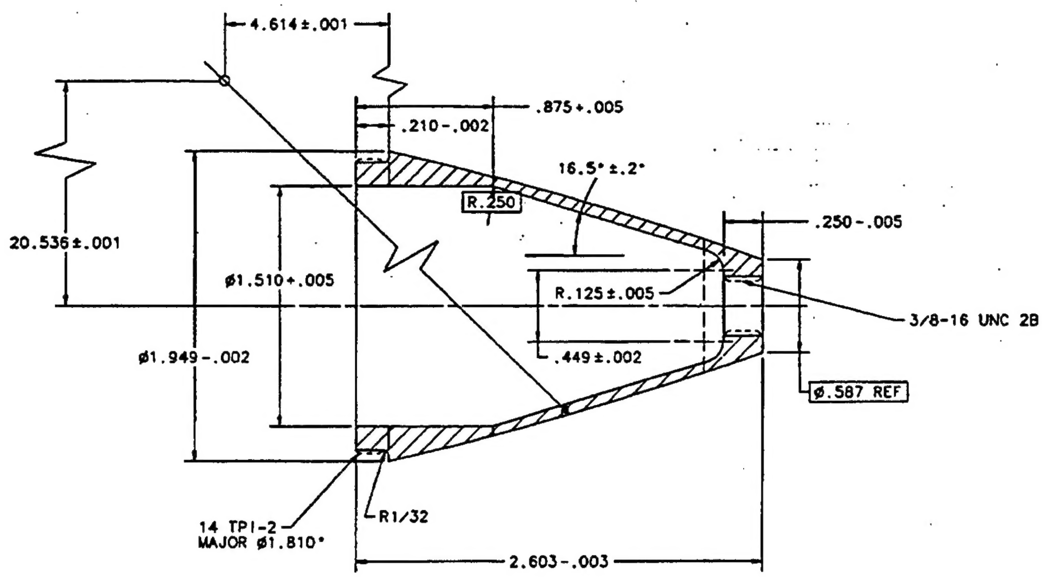

Figure 2. Schematic of a D-Fuze Windshield.

2. Background

Table 1 displays the material properties of various materials used in this study. These materials specifically are

- Nylon 66, which is unfilled. This semi-crystalline material is very common with a variety of manufacturers.
- Nylatron® GSM Blue contains finely distributed particles of molybdenum disulphide to enhance its bearing and wear behavior without impairing the impact and fatigue resistance inherent in unmodified cast nylon grades (http://www.dsmepp.com/products/europe/nylons_europe.html# nytr gsm).
- Unfilled polycarbonate is a thermoplastic resin that is very common with a variety of manufacturers such as General Electric or Bayer.
- Cycolac® acrylonitrile butadiene stryrene (ABS) is an unfilled thermoplastic consisting of (poly)ABS.
- Zytel® ST801HS is an unfilled heat-stabilized toughened nylon.

- Ultem® 1000, an unfilled amorphous polyetherimide, is manufactured by General Electric Plastics.

- Ultem® 2300 is an amorphous polyetherimide, with 30% glass reinforcement.

- Victrex® polyetheretherketone (PEEK™), with 40% glass fiber reinforcement, is a polyetheretherketone, glass-reinforced, semi-crystalline polymer.

- Polyimide has 40% glass fiber reinforcement. This particular combination is available at RTP company.

Table 1. Material Properties of Studied Polymers

	Nylon 6/6	Nylatron® GSM Blue	Polycarbonate Unfilled	Cycolac® AR ABS	Zytel® ST801HS	Ultem® 1000	Ultem® 2300	PEEK™ 40% long glass fiber	Polyimide 40% glass fiber
Property									
Specific Gravity	1.15	1.15	1.28	1.04	1.15	1.28	1.51	1.62	1.63
Flexural Modulus of Elasticity (psi)	450,000	500,000	350,000	345,000	150,000*	500,000	800,000	2,000,000	1,750,000
Flexural Strength (psi)	15,000	15,000	13,000	11,748	N/a	20,000	30,000	40,000	41,000
Heat Deflection Temperature 264 psi (F)	200	N/A	290	172	158	392	410	>500	630
Tg-Glass Transition (amorphous) (F)	N/A	N/A	293	N/A	N/A	419	419	N/A	N/A
Melting Point (crystalline) (F)	500	520	N/A	N/A	500	N/A	N/A	N/A	N/A
Water Absorption Immersion, 24 hours % by wt.	0.3	.22	.2	N/A	N/A	0.25	0.18	0.1	0.08
Dielectric constant, 106 Hz	3.6	N/A	3.17	N/A	N/A	3.15	3.7	N/A	3.6

Materials such as Nylatron®, polycarbonate, Zytel®, and cycolac® were previously used in windshield fabrication. These materials were thought to be less durable to launch stress or to areo-dynamic heating. An early drawing schematic of an injection molded windshield, dated 1972, required Zytel®, which is a modified nylon. Other early windshield designs required injection molded cycolac®. Apparently, because of low volume production runs and the costs of molds, injection molding was discarded, and fabrication of the windshields required machining from previously extruded or cast bar stock material. Current fabrication is based on available bar stock material. Based on this, PEEK™ and polyimide, both with 40% glass, were eliminated because they were too expensive for distributors to stock.

In addition to mechanical, electrical, and thermal properties, water absorption was examined. The asterisk (*) on the Zytel® flexural modulus of elasticity indicates that this quantity was measured in 50% relative humidity. With less water absorption (0.2% moisture content by weight), mechanical properties improve significantly. The flexural modulus is on the order of 250,000 psi.

3. Experiment

3.1 Windshield Crush Experiments

Experiments consisted of crushing windshields of very similar geometries, yet different materials. In addition, three-point flexural investigation of Ultem® 1000 and 2300 material was performed as a verification. Crushing was performed with an Instron 4505 frame. The windshield was placed between the platens, and the cross-head speed was set for 0.05 in./min. Data were acquired with Series IX™ software.

Several nylon 66 windshields were crushed to determine repeatabilty of the experiment. Figure 3 shows the linear regions of those experiments.

Two experiments used windshields from an old fabrication run, and the other two came from a newer run. No significant difference was observed, so all the plots were averaged. Data from the average curve were used to calibrate a finite element analysis (FEA) of the nylon 66 windshield. The modulus of elasticity was adjusted until the model results correlated with the linear crush experiment average results. The FEA indicated that the nylon 66, which has a modulus of 450,000 psi, based on ASTM 790 standard, had a reduced modulus of 260,000 psi. The reason for this is because of the moisture absorption of nylon 66. Water degrades the strength of nylon 66 by interfering with the hydrogen bonds of the polymer (personal communications, Steve McKnight, ARL, April 2001). In addition, the moisture causes swelling of the material, which makes it difficult to

maintain dimensional tolerances. The hygroscopicity of the nylon 66 caused the windshields to absorb moisture within days. During fabrication runs, the windshields fit the aluminum nacelles and passed the acceptance check. Yet, when a D-fuze was assembled, the parts no longer fit together, requiring effort of the assembler to screw the windshield onto the nacelle.

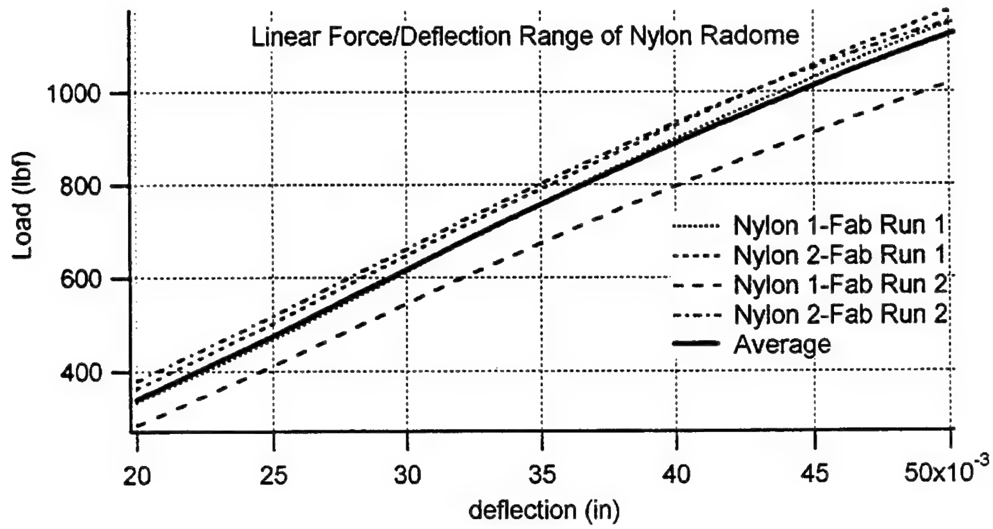

Figure 3. Linear Force Deflection Range of Nylon 66 Windshield Crush Experiments.

Based on the newer modulus, the amount of blow-by pressure that the nylon 66 windshield could survive was 750 psi. The need for a new windshield design became apparent. However, packaging design constraints dictate that the geometry could not change significantly. What was needed was a material change and a manufacturing change.

Several polymers were considered to replace nylon 66. Most of these materials were not readily available in cylinder stock but were available in pellet form for use in injection molding. The injection molding of the windshield with glass-filled resins could provide an improvement in mechanical properties. This process would orient the glass fibers in the axial direction of the windshield, allowing for more strength against buckling (personal communications, Thomas Mulkern, ARL, April 2001). However, because of the limited quantity of the fabrication runs, injection molding was too expensive. The one material in this study that was readily available in cylinder stock was Ultem® 2300. A quick fabrication run of the windshield design with this material was performed. As one can see in Figure 4, the nylon 66 did not fare as well as the other materials. The newer material, Ultem® 2300, did extremely well.

Based on Figure 4, one can see a drastic improvement in the strength of the windshield. The new windshields were assembled with the D-fuzes and were fired in the same type of flight experiment in which the nylon 66 windshields failed. The amount of blow-by pressure from both series of experiments has not been quantified, but the Ultem® 2300 windshields survived.

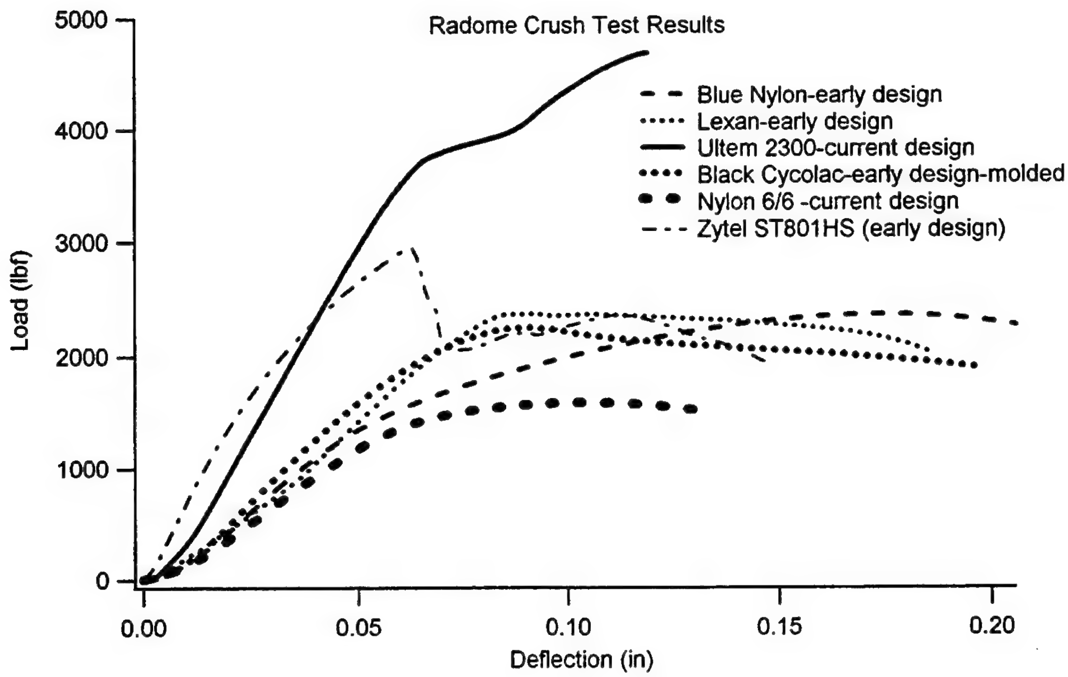

Figure 4. Radome Crush Experiment Results.

3.2 Three-Point Bending Experiments

As a verification, three-point bending experiments were performed on Ultem® 1000 and 2300 to verify the actual flexural modulus of elasticity of the specific stock from which parts were being made. Early cross-referencing of various data sheets for Ultem® 2300 indicated a significantly varying flexural modulus, even though the same standard (ASTM D790) was used. Since Ultem® 2300 contains 30% glass fibers, this report surmised that the thinner the specimen became, the less glass content in the matrix; therefore, at some thickness, the glass-filled resin should behave like the unfilled resin. Each experiment contained four or five evaluated specimens. Table 2 displays the results of the experiments.

All these specimens were taken from the same piece of 2-inch bar stock. Also, the specimens were cut from a 1- by 1-inch area in the center of the stock. Specimens were also cut lengthwise with respect to the axis of the bar stock. As one can see, the variation in flexural modulus of elasticity between the 0.125- and 0.0625-inch specimens would indicate a non-uniformity with which the fibers are dispersed. The interior region was initially chosen for specimen harvest because the fiber orientation was thought to be more random as opposed to being aligned axially

nearer the surface of the extruded stock. An average of the two moduli would be 814,500 psi, which is very close to what the specification sheet indicates.

Table 2. Flexural Bending Experimental Results

	Ultem® 2300 0.125 in. thick	Ultem® 2300 0.0625 in. thick	Ultem® 2300 0.03125 in. thick	Ultem® 1000 0.0625 in. thick	Ultem® 1000 0.03125 in. thick
Average properties					
Displacement at Yield (in.)	0.300	0.132	0.100	0.178	0.109
Stress at yield (psi)	28,100	36,400	26,500	31,300	22,200
Strain at yield (in./in.)	0.056	0.050	0.075	0.067	0.081
Flexural Modulus of Elasticity (psi)	670,000	959,000	486,000	628,000	343,000

As the Ultem® 2300 specimen becomes thinner, the results show that the flexural modulus is the same as for unfilled Ultem® 1000. This may indicate that the fiber content in the sample is so low that the filled resin may as well be unfilled. The point of this is that if a design requires a certain thickness in the geometry, an unfilled resin may not be warranted specifically for Ultem®.

4. Conclusion

A cursory study has been performed on selected extruded bar stock polymers, which are readily available for machining windshields for D-fuzes of various geometries. Ultem® 2300 appears to provide the best mechanical, thermal, and electrical properties of the studied polymer materials. However, depending on the thickness of the geometry, a designer may want to reconsider using unfilled Ultem® 1000. If the cross section of the geometry reduces to a range near 0.03125 inch, there may not be enough glass fiber to reinforce the polyetherimide matrix. Further literature research indicated that the ogive of the M762 fuze is made from injected molded polyetherimide with 30% glass filler.

5. Future Work

Another empirical means of validating the analyses, such as subjecting the windshields to a static pressure load until failure, should be performed. More intensive efforts to find higher performance material solutions for the design of windshields for future combat system-like projectile launch and flight conditions. Materials that have functional temperatures in the region of the adiabatic wall temperatures of supersonic and hypersonic vehicles need to be studied. Some of these materials may be ceramics, composites, and other polymers. Antenna radiation patterns and intensity measurements of the material and the geometry also need to be made. In addition, fabrication procedures should be studied. To achieve the best material properties from an engineered polymer, the parts should probably be injection molded rather than machined from a stock shape.

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APPENDIX A

STYCAST® 1090 SI ELECTRO-MECHANICAL PROPERTIES VERIFICATION

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STYCAST® 1090 SI ELECTRO-MECHANICAL PROPERTIES VERIFICATION

Recently, the author was asked to look into the effects of moisture absorption on Stycast® 1090 SI. Stycast® 1090 SI is a low density, syntactic foam, epoxy encapsulant, which is commonly hardened with the 23LV catalyst. ARL frequently encapsulates electronics with Stycast®. The encapsulation, however, is not performed in desiccated laboratory conditions. There were concerns that the resin might be inherently hygroscopic or that moisture might enter during the mixture process, which could degrade electrical and/or mechanical properties. Even though the manufacturer (Emerson and Cumings) claims that the moisture absorption is negligible, simple electrical and mechanical property measurements were made to verify the manufacturing properties.

First, a determination of the dielectric constant and the loss tangent was made on a sample of cure Stycast®. The epoxy had been hardened for more than 24 hours at 25° C and 50% to 70% humidity. The experiment used a coaxial probe technique with a Hewlett-Packard 85070B measurement device. The dielectric measurement was from 0.2 GHz to 3 GHz. The dielectric constant ranged from 2.5 to 2.4 and the loss tangent averaged 0.033 for this range. The specification sheet has dielectric constants in increments: 60 Hz, 1 kHz, and 1 MHz, with the respective dielectric constants as 3.7, 3.1, and 2.9. The experimentation method for the specification sheet is ASTM D150. The downward trend indicates that the dielectric constant might be ~2.5 at 1 GHz, and this agrees with the specification sheet, even during the environmental conditions. The loss tangent averaged 0.01 to 0.02 for the same increments, which puts the results in close agreement with the specification sheet.

Second, a three-point bending experiment that employs ASTM D-790 standards was used to measure flexural stress and flexural modulus of elasticity. Specimens were created as per the ASTM requirements during 25° C and 50% to 70% humidity environmental conditions. Unfortunately, the specification sheet does not include the flexural modulus of elasticity. The manufacturer was queried for this property but they declined. The only property available to compare was the flexural strength. However, there were two values for this property of Stycast® 1090, with the 23LV catalyst. Again, the manufacturer was queried, but no response has been made. The two values listed for flexural strength are 4000 psi (28 MPa) and 6900 psi (48 MPa). The experiment used seven samples, of which, the average flexural strength was 7070 psi (49 MPa). Based on both specifications, the Stycast® does not appear to lose any strength.

In conclusion, Stycast® 1090 SI appears to maintain the manufacturer's specifications for dielectric constant, loss tangent, and flexural strength under fluctuating temperature and humidity. Since "...most materials today are tested at 1 MHz,...there is still a lot of uncertainty about how materials perform at

2.4 GHz" [2]. The electrical experiment verifies the dielectric properties of Stycast® at high frequency.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Pursuant to a previous report [1], an effort has been made to continue to find higher performance materials for the design of windshields. A product that the U.S. Army Research Laboratory provides the test and evaluation community is a yawsonde, now termed "diagnostic fuze" or "D-fuze". This device is capable of sensing the inertial environment of a cannon-launched projectile and telemetering the live data to a ground station. In order to telemeter data in flight, the antenna has to radiate through a protective windshield. This windshield is not only transparent to radio frequency radiation but is also a means of ballistic and thermal protection.

A recent flight experiment with a prototype artillery projectile revealed a weakness of the nylon 66 windshields to "blow-by[1]" gases. The windshields were designed to survive aero-pressures attributable to Mach 3 launch and flight with a significant safety factor. However, blow-by effects were never considered.

A cursory study has been performed on selected extruded bar stock polymers, which are readily available without our having to consult a compounding source, for machining windshields for D-fuzes of various geometries. Ultem" 2300 appears to provide the best mechanical, thermal, and electrical properties of the studied polymer materials. However, depending on the thickness of the geometry, a designer may want to reconsider using unfilled Ultem" 1000. The cross section of the geometry reduces to a range near 0.03125 inch; there may not be enough glass fiber to reinforce the polyetherimide matrix. Further literature research indicated that the ogive of the M762 fuze is made from injected molded polyetherimide with 30% glass filler.

[1]Propulsion gases that leak past the projectile's obturator. In addition to the air already being pushed by the launching projectile, these gases increase the total pressure on the windshield.

14. SUBJECT TERMS

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